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LINEAR COMPRESSIONS TO 30,000 kg/cm², INCLUDING RELATIVELY INCOMPRESSIBLE SUBSTANCES

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Introduction

This paper continues the program of measurement of linear compressions to 30,000 kg/cm^2, for which results for 16 comparatively compressible substances have already been published.[1] The particular object of these measurements is to obtain as accurately as possible the deviations of the compression from linearity with pressure. The substances measured formerly were relatively compressible; it was desired to now extend the measurements to less compressible substances. Formerly, measurements of sufficient accuracy for the purpose in hand did not put too stringent demands on the apparatus. Some 25 unsuccessful attempts showed, however, that the former apparatus was not adequate for many of the more incompressible substances, so that the first task in extending the measurements to such substances has been to refine the apparatus.

The refinement of the apparatus proved to be a more serious undertaking than had been anticipated, and much time was spent in the preliminary work. Furthermore, more time was spent in the work of development than would otherwise have been necessary because of my preconception about the nature of the physical situation. This preconception was that the relation between linear dimensions and pressure for ordinary substances would be smooth and single valued, so that the smoothness of the results could be used as a criterion of the satisfactory functioning of the apparatus. After exhaustive checking, the conclusion seemed to be forced that for many substances the relation is not smooth, but there are small-scale irregularities characteristic of the particular substance, which can never be made to vanish. On reflection it is perhaps not unnatural that this should be the situation, when the magnitude of the pressures and the practical impossibility of obtaining any actual substance in a truly homogeneous condition are considered. That this is the case, however, makes much more difficult the task of obtaining truly significant values for

the second and higher order terms in the compression of the incompressible materials, and places the theoretical physicist who must use the experimental results under a corresponding embarrassment. The difficulty is greatest for the relatively hard materials of this paper, which are at the same time relatively incompressible. There is comparatively little uncertainty in the deviations from linearity of the softer materials, since for these materials the irregularities are small compared with the deviations from linearity.

The materials measured in the following are in many cases the identical specimens which have previously been measured over a narrower pressure range, usually up to 12,000 kg/cm^2. A number of the elements, however, are of more recent origin. With the completion of this paper nearly all the specimens of inorganic materials which were formerly measured in the range to 12,000 kg/cm^2 have now been measured in the range to 30,000. A few of the former specimens were unavailable because of accidents of one sort or another.

In the following the more compressible specimens were measured with the lever piezometer of the former paper, the new more sensitive piezometer not being adaptable for them. The dividing line is approximately at aluminum, all substances more compressible than this being measured with the former piezometer. The materials may be classified as elements (pure metals), alloys and intermetallic compounds, and minerals, many of them in the form of single crystals, and a few organic single crystals.

The Apparatus and Method

The new apparatus is the "lever piezometer" of my former work,[2] improved in two essential respects. In this apparatus the specimen rests against the short arm of a lever, the angular position of which alters when the relative dimensions of the specimen and the housing of the lever change under the differential compression brought about by the application of hydrostatic pressure to the fluid medium in which all parts of the apparatus are immersed. The motion of the long arm of the lever is measured in terms of the alteration of resistance of a wire attached to it and sliding over a cross wire attached to the housing. It is evident that the lever itself must be positive in its action, without backlash or other indefiniteness, and that the surface of the measuring wire and the cross wire must be smooth. The improvements consist in the use of a more uniform slide wire and in a better method of pivoting the lever.

With regard to the wire, a simple consideration will indicate the degree of perfection required in the surface. The electrical parameters of the potentiometer circuit with which the resistance of the

slide wire was measured were such that a relative shortening of 2×10^{-6} cm of specimen with respect to the housing could be detected. This corresponds to the effect of 10 kg/cm^2 on platinum. Since the magnifying power of the lever was about 10, this demands that there be no scratches or other surface imperfections as much as 2×10^{-5} cm wide on the wire. Otherwise the readings will jump spasmodically when the scratch moves across the cross-wire. This of course presupposes that the material of the wire underneath its surface is uniform to a corresponding degree. In the former work the wire had been made of nichrome. This had been obtained from the manufacturer, The Driver Harris Company. Its diameter as purchased was 0.016 inch, and it was drawn down further to 0.013 inch in several stages through special diamond dies. The wire so drawn was examined microscopically and calibrated electrically for uniformity, and the best portions used in the piezometer. This was sufficiently good for the former measurements. However, the surface of this wire disclosed blemishes under the microscope which could never be got rid of. In the attempt to eliminate them for the present work, the wire was subjected to various processes of preliminary polishing or grinding, some of them rather elaborate, before the final drawing, but without success. Finally, half a dozen different sorts of high resistance wire made by Driver Harris were examined to find if any were superior to nichrome. I am indebted to the manufacturers for selecting coils which were especially smooth. These wires were then further drawn in the machine shop of the laboratory from 0.014 to 0.013 inches in a new diamond die specially made and polished for this work. This drawing was done in the lathe, by attaching the wire to the screw cutting feed, a device which I owe to the suggestion of my mechanic, Mr. Charles Chase. Drawing by hand is too jumpy and irregular. The wires so made were mounted in the calibrating device and their uniformity studied. Of the various alloys tried, "Iconel" or "Nirex" proved the best and much superior to Nichrome. This alloy is composed of 13% Cr, 8% Fe, balance Ni. The various constants of this material, specific resistance and compressibility, were determined and found to be not far from those of nichrome, so that only minor changes were required in the various correction terms. Its temperature coefficient of resistance is also so small as to introduce no error under the conditions of use.

The second major improvement concerns the pivoting of the lever. Formerly the lever rocked on two hardened steel points, pressed by a spring into a crater and notch. The points, of course, were really portions of spheres with finite radius and the bearing against crater or notch was on two tangents. The point of leverage was therefore

indefinite by a possible maximum of the distance of separation between the tangents. At the two points of contact angular motion necessarily involved surface slip and friction with resultant lack of perfect definiteness and reproducibility. The improvement consisted of replacing the steel points with a flat steel spring clamped between hardened clamps, as shown in Figure 1. Not only does the flat steel spring replace the former pivoting points, but it also eliminates the necessity for the spring by which the points were formerly maintained in contact with their seats. This improvement in design permits such an alteration of proportions that the multiplying power of the lever could be increased from approximately 5 to approximately 10. The flat spring in the final form was 0.007 inches thick; this thickness was arrived at by trial. The force exerted by this spring necessarily varies with the displacement of the lever. By measurement it was found that the maximum variation in the force at the end of the long arm, corresponding to the most compressible of any of the substances in the following, was from 2 to 6 ounces. Taking account of the multiplication and cross section of the specimen, this corresponds to a maximum change of 30 kg/cm^2 in the one-sided compressional force exerted on the specimen by the method of mounting; this is negligible compared with the maximum pressure of 30,000.

The contact between the specimen and the short arm of the lever was still by a hardened steel "point" resting in a hardened crater. To make this contact as definite as possible the "point" was made in the form of the three-quarter portion of a sphere of radius .005 inch, made with a special tool and shown in Figure 2, highly polished.

The full dimensions of the specimen taken by the piezometer were 0.75 inches in length and 0.20 inches in diameter. For some specimens the diameter was reduced to 0.18. In some cases, particularly with single crystals of minerals, the full length was not available. In these cases a shorter specimen was used extended by a piece of American ingot iron, the compression of which is known.

The lever piezometer thus constructed was calibrated much as before. The short arm was moved a known distance with a Brown and Sharpe high-precision micrometer screw, cut on a specially large barrel and provided with a head graduated to 0.0001 inch and reading by estimation to 0.00001 inch. The multiplying power was determined by measuring simultaneously the motion of the long arm with a suitably mounted microscope, and the changes in potentiometer setting due to the motion of the slide wire. The piezometer was mounted in a temperature bath for this purpose. These measurements established the sufficient uniformity of the slide wire and the

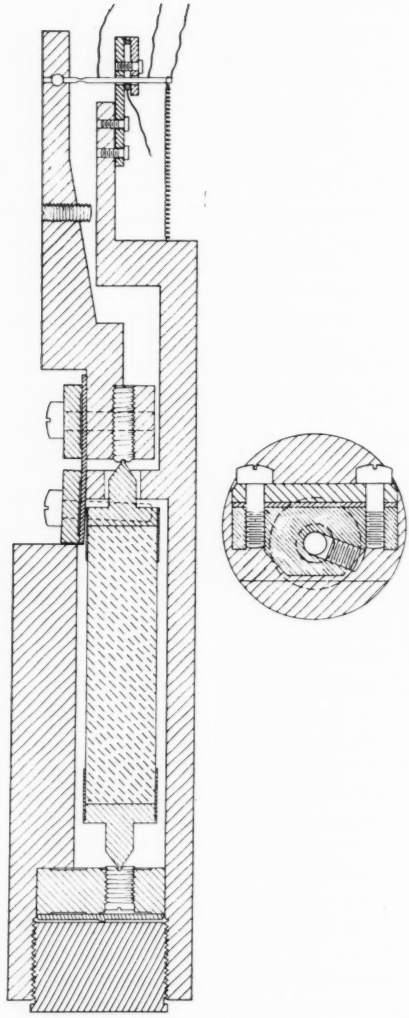

FIGURE 1. The modified lever piezometer, with spring replacing pivots.

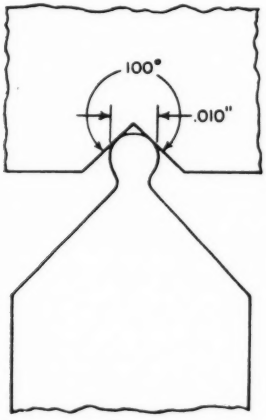

FIGURE 2. The ball contact for the specimen.

linearity of the relation between motion of short arm and the slide wire.

The calculations and corrections were essentially as before and need not be described further. Special measurements had to be made of the effect of pressure on resistance of Nirex and also of its compressibility. The latter will be described presently. The pressure coefficient of resistance, terminals attached to the wire, was -2.82×10^{-7}, pressure in kg/cm^2 units.

Even after the major improvements had been effected, the piezometer did not at once function satisfactorily and some 20 preliminary runs were made incorporating various minor refinements. The most important of these was a three-point contact between the mounting and the block supporting the lower end of the specimen. This block contained a screw adjustment by which the absolute position of the specimen could be altered so as to bring into operation one or another part of the slide wire. It was established that there was no dependence of the pressure effects on the absolute setting on the wire. It was also necessary to so design the apparatus as to avoid all regions where liquid might be entrapped, as between the rounded end of the pivot and its seat; otherwise irregular effects were produced by nonhydrostatic components of stress.

It has already been stated that irregularities persisted after all improvements; the outstanding irregularities were finally ascribed to the specimens themselves rather than the apparatus. A detailed

presentation of all the evidence on which this conviction rests would take too much space to be feasible. In brief, the argument rests on the discovery of patterns characteristic of the individual materials which persist through variations in the treatment given the specimen. Often these patterns were irregular, but the argument was much strengthened by the existence of substances with smooth patterns. Of special and decisive significance was the behavior of four different specimens of martensite with progressively different heat treatments. These all exhibited hysteresis loops, the readings not being single valued with pressure but lying on different curves for increasing and decreasing pressure. The individual points lie smoothly, within limits of 2 and 3 times the maximum sensitiveness of the potentiometer, on one or other branch of the hysteresis loop, and there is a consistent variation in the width of the loop with the heat treatment.

It was a matter of extraordinary good fortune that soft iron itself is one of the substances which not only does not exhibit hysteresis but also for which the results are smooth. This smoothness is characteristic of several grades of iron investigated, namely American ingot iron, for which the fiducial absolute determination of compressibility has already been made,[3] a single crystal of pure iron, and a pure carbonyl iron. The results for these three grades of iron were very close to each other. Since the piezometer itself is made of iron and since the measurements with the lever piezometer are all differential, it is obvious that irregularity in the iron itself would have seriously limited any information to be obtained.

In addition to the characteristic patterns of minor deviation from linearity, irregular or smooth, a number of substances showed an entirely different sort of thing, namely cusps or breaks in the direction of the tangent (transitions of the second kind) which have been found before for other more compressible substances[4] and which are doubtless of more fundamental physical significance.

The results now follow. In most cases the irregularities are so small that the mean results are given, smoothing over the irregularities, but with a statement of the nature of the irregularities including any consistent dependence on previous treatment of the specimen. Some quantitative indication is attempted of the magnitude of the irregularities by giving the average deviation of a single reading from a smooth curve. This is given in percentage of the total shortening of the specimen under the maximum pressure instead of as percentage of the differential shortening, as has been the practice in some previous papers. The present practice is obviously better adapted to the materials of this paper, which include substances with nearly the same compressibility as iron and therefore with a differential shortening

which on occasion may become vanishingly small. In general, a run consisted of 18 readings at regular pressure intervals with increasing and decreasing pressure, the decreasing readings being staggered between the increasing readings. Before the run the sample was seasoned by several applications and release of pressure. The seasoning routine was in almost all cases the same. Unless it is specially mentioned it is to be understood that the preliminary seasoning was by three applications of 30,000 kg/cm^2 at room temperature.

The arrangement is: elements, alloys and intermetallic compounds, minerals, and organic crystals. Within each group the arrangement is by increasing compression under the maximum pressure. All measurements were made at room temperature, which varied from 23° to 26°. In the measurements and calculations, one more significant figure was used than is retained in the tables. The results are reproduced by tabulating volume decrements, or decrements of length, at intervals of 5,000 kg/cm^2. In view of the diversity of the results this seemed better than attempting to reproduce them by an analytical formula, although in many cases a second degree expression would have sufficed. In some cases, when the hysteresis pattern was especially prominent, the results with increasing and decreasing pressure separately are reproduced. The volume decrements listed in the tables were calculated from the measured changes of length, retaining second-order terms. That is, for an isotropic substance,

$$|\Delta V/V_0| = 3\,|\Delta l/l_0|\,\{\,1 - |\Delta l/l_0|\,\}\,,$$

with corresponding expressions for non-cubic crystals.

The Results

Elements

Iridium. This material I owe to the courtesy of Baker and Company, who fabricated it especially and loaned it to me for the measurements. The original slug was "worked from a sintered powder-metallurgy bar." Baker and Company described the density of a bar so formed as "practically 100%." It was 0.180 inches in diameter and 0.75 inches long; it was ground from the sintered slug. After receiving it the ends were trued flat and parallel by lapping. The results are given in Table I. The average deviation of a single reading from a smooth curve was 0.6 per cent of the shortening at the maximum. The irregularities showed no consistent pattern; in particular there was no appreciable hysteresis. It will be noticed that within the limits of error the relation between pressure and volume decrement is linear. The relation between change of length and pressure was, however, distinctly not linear, with curvature in

TABLE I

COMPRESSION OF ELEMENTS

Pressure kg/cm²	Iridium	Tungsten $\Delta V/V_0$		Ruthenium	Platinum	Molybdenum	Rhodium	Tantalum $\Delta V/V_0$		Cobalt, single crystal		
	$\Delta V/V_0$	Single Crystal	Drawn Rod	$\Delta V/V_0$	$\Delta V/V_0$	$\Delta V/V_0$	$\Delta V/V_0$	99.9%	99.95+%	$(\Delta l/l_0)_{\parallel}$	$(\Delta l/l_0)\perp$	$\Delta V/V_0$
5,000	.00137	.00155	.00152	.00154	.00176	.00179	.00180	.00244	.00243	.00087	.00083	.00253
10,000	.00272	.00309	.00301	.00312	.00351	.00357	.00361	.00488	.00485	.00172	.00166	.00504
15,000	.00408	.00475	.00458	.00477	.00526	.00536	.00540	.00728	.00726	.00260	.00251	.00760
20,000	.00545	.00634	.00612	.00645	.00701	.00714	.00719	.00969	.00967	.00347	.00331	.01006
25,000	.00683	.00797	.00765	.00818	.00877	.00891	.00896	.01208	.01208	.00434	.00412	.01253
30,000	.00818	.00959	.00917	.00989	.01048	.01064	.01071	.01447	.01448	.00520	.00490	.01492
Percentage Deviation from Smooth Curve	0.61	0.85	0.60	0.80	0.69	0.61	0.65	0.12	0.16	0.13	0.30	

Pressure kg/cm²	Nickel	Palladium	Gold	Columbium $\Delta V/V_0$		Iron $\Delta V/V_0$			Copper	Titanium
	$\Delta V/V_0$	$\Delta V/V_0$	$\Delta V/V_0$	Increasing	Decreasing	American Ingot	Single Crystal	Carbonyl	$\Delta V/V_0$	$\Delta V/V_0$
5,000	.00277	.00267	.00281	.00289	.00276	.00289	.00289	.00288	.00353	.00449
10,000	.00479	.00517	.00558	.00569	.00556	.00575	.00575	.00572	.00696	.00900
15,000	.00750*	.00761†	.00831	.00842	.00836	.00856	.00856	.00853	.01039	.01332
20,000	.01001	.01015†	.01101	.01115	.01113	.01133	.01133	.01130	.01370	.01810
25,000	.01262	.01273	.01367	.01386	.01385	.01407	.01407	.01402	.01695	.02174
30,000	.01515	.01522	.01626	.01649		.01676	.01676	.01667	.02010	.02581
Percentage Deviation from Smooth Curve	0.12	0.18	0.03	0.014		0.012	0.012	0.015	0.14	0.58

*Cusp at 10,500 †Cusp at 16,500

TABLE I (Continued)
COMPRESSION OF ELEMENTS

Pressure kg/cm²	Silver	Silicon	Beryllium	Germanium	Aluminum	Antimony Single Crystal			
	$\Delta V/V_0$	$\Delta V/V_0$	$(\Delta l/l_0)\perp$	$\Delta V/V_0$	$\Delta V/V_0$	$(\Delta l/l_0)\perp$	$(\Delta l/l_0)_{8°}$	$(\Delta l/l_0)_{\parallel}$ Calc.	$\Delta V/V_0$
5,000	.00473	.00491	.00158	.00623	.00668	.00232	.00770	.00789	.01248
10,000	.00938	.00965	.00309	.01237	.01312	.00466	.01402	.01498	.02414
15,000	.01385	.01433	.00460	.01826	.01932	.00688	.02008	.02144	.03486
20,000	.01820	.01888	.00604	.02394	.02520	.00897	.02550	.02722	.04459
25,000	.02236	.02332	.00745	.02950	.03090	.01103	.03055	.03262	.05384
30,000	.02619	.02755	.00878	.03488	.03642	.01299	.03522	.03760	.06243
Percentage Deviation from Smooth Curve	0.27	0.18	0.41	0.28	0.26	0.40	0.48		

Pressure kg/cm²	Zinc Single Crystal			Thorium	Tin Single Crystal			Tellurium Single Crystal		
	$(\Delta l/l_0)\perp$	$(\Delta l/l_0)_{\parallel}$	$\Delta V/V_0$	$\Delta V/V_0$	$(\Delta l/l_0)\perp$	$(\Delta l/l_0)_{\parallel}$	$\Delta V/V_0$	$(\Delta l/l_0)\perp$	$(\Delta l/l_0)_{\parallel}$	$\Delta V/V_0$
5,000	.00076	.00644	.00794	.00933	.00289	.00314	.00889	.01113	−.00222	.02011
10,000	.00151	.01277	.01575	.01733	.00561	.00621	.01732	.02138	−.00390	.03915
15,000	.00227	.01849	.02293	.02472	.00819	.00915	.02530	.03002	−.00512	.05551
20,000	.00303	.02376	.02967	.03188	.01065	.01192	.03283	.03726	−.00603	.06943
25,000	.00381	.02879	.03618	.03882	.01304	.01455	.04004	.04384	−.00667	.08234
30,000	.00459	.03356	.04242	.04555	.01534	.01704	.04691	.04946	−.00720	.09346
Percentage Deviation from Smooth Curve	0.50	0.54		0.45	0.37	0.38		0.57	0.52	

the "abnormal" direction, that is, a linear compression increasing more rapidly than linearly with pressure. The compression of Ir has been formerly measured[5] to 12,000. The former compression at 10,000 at 25°, using the 1940 compression of iron,[6] was .00268 against .00272 found now.

Tungsten. Measurements were made on two specimens. One was drawn rod obtained in 1939 from the Fansteel Metallurgical Corporation and described by them as of 99.9 +%, R_2O_3 .002% maximum, purity. This had been used in several of the preliminary measurements and had been exposed to four applications of the maximum pressure before the measurements recorded here. The other specimen was a single crystal, which I obtained through the courtesy of Dr. Irving Langmuir some 25 years ago. It was made by the German General Electric Company by prolonged resistance-heating the sintered rod in vacuum until it recrystallized into a single crystal, as indicated by the reflection pattern from the surface. The original diameter was about 0.25 inch. During the recrystallization process it had sagged a little from its own weight between the electrodes on which it rested. The specimen used above was ground out of this crystal so as to be straight. This is the same crystal on which I have previously made measurements, in particular of the elastic constants.[7] This single crystal was measured once to the maximum before the measurements recorded in Table I. The table indicates a greater experimental irregularity for the single crystal than for the drawn rod. The compression of the latter is distinctly less than for the crystal, and is sensibly linear in pressure. The single crystal, on the other hand, deviates from linearity in the abnormal direction. This is doubtless connected with its larger compressibility, and indicates the presence of internal inhomogeneities, which is not surprising in view of the method of formation. The irregularities for the drawn rod followed no definite pattern. For the crystal, on the other hand, there was definite hysteresis, and the width of the hysteresis loop was about twice as great on the first application of pressure as on the second. Furthermore, the hysteresis was in the abnormal direction, the shortening being in advance of the pressure instead of lagging behind it. The maximum width of the hysteresis loop on the second application of pressure was about 2.3 per cent of the maximum distortion. The value previously obtained[7] for the compression at 10,000 for the identical crystal corrected for the 1940 value of iron was .00317 against .00309 above. The corrected former results also indicated a second degree term of abnormal sign.

Ruthenium. This was a swaged rod, obtained some 25 years ago from Johnson and Mathey of London, and already measured[8] to 12,000 kg/cm^2. "It was not perfectly regular in appearance, but appeared as if there might be seams in it." The irregularities in the pressure effects were unusually large. There is a hysteresis loop of abnormal sense of maximum width equivalent to nearly 6 per cent of the maximum distortion. There were large initial irregularities; the initial points were discarded in the calculation of the average deviations. The relation between volume compression and pressure fails to be linear by an unusually large amount in the abnormal direction. Previous measurements on the identical specimen to 12,000 yielded for the corrected compression at 10,000 .00333 against .00312. Altogether, the indication is of an abnormally high state of internal strain brought about by the increased pressure range.

Platinum. This was a recent specimen, obtained on loan from Baker and Company. It was worked from a casting. The preliminary treatment was the same as for iridium, already described. The deviation pattern indicates a definite hysteresis of the normal sign, the maximum width of the loop being 1.2 per cent of the maximum distortion. The compression deviates slightly from linearity with pressure in the normal direction. The former value[9] of the compression at 10,000 corrected for the 1940 iron and measured on another sample over the range to 12,000, was .00355 against .00351 found now.

Molybdenum. This was rod, obtained in 1939 from the Fansteel Metallurgical Corporation and described by them as of purity 99.9 + %, Fe 0.005% Maximum, C none. It had been subjected to several preliminary applications of pressure in measurements during the development of the apparatus. The pattern of deviation indicates a normal hysteresis loop of width 1.2 per cent of the maximum distortion. The deviation of the compression from linearity with pressure is definite and in the normal direction. The former compression[10] at 10,000 corrected for the 1940 iron, and measured on another specimen over the range to 12,000 was .00361, against .00357 above.

Rhodium. This was obtained on loan from Baker and Company at the same time as the iridium and platinum. It was annealed and had been formed by casting and worked to dimensions by grinding. The preliminary treatment was the same as for the other two. The pattern of deviation from linearity indicates a very small hysteresis in the normal direction of the order of one per cent of the maximum distortion, but the loop is pretty well obscured by the other irregu-

larities. The deviation from linearity is in the normal direction. The former compression[11] at 10,000 corrected to the 1940 value of iron, on a specimen obtained from Johnson Mathey measured over the range to 12,000, was .00345 against .00361.

Tantalum. Measurements were made on two specimens, the first obtained from the Fansteel Company in 1939 and said to be of 99.9% purity, Fe 0.01% Maximum, C 0.003% Maximum, and the second obtained from the same source in 1946 and said to be of slightly greater purity, 99.95%. Both had been annealed by the Company. This material was rather extensively investigated in the preliminary measurements, the pattern of irregularity being pronounced and characteristic. The first specimen was subjected to six applications of 30,000 and the second to two applications before the final measurements. Through all these applications there was a persistent hysteresis in the normal direction. The width of the loop on the final application was 1.04 per cent of the maximum distortion for the first specimen and 0.97 per cent for the second. The loop is so definite that the deviations of a single point from the smooth curve given in Table I are deviations from the two branches of the loop, instead of deviations from the mean curve drawn through the center of the loop, as has been the case for the previous metals. The compressions listed in Table I are, however, the compressions corresponding to the mid-curve of the loop. It will be noticed that the deviation from linearity, that is, the second order term in the compression, is less for the purer of the two specimens. This specimen had not been so well seasoned as the other, however, and its hysteresis loop was definitely not completely closed at the lower end. It is probable that the second order term of the less pure sample should be given greater significance. The former compression[12] at 10,000 corrected for the 1940 Fe, measured on a specimen obtained from Fansteel before 1923 in the range to 12,000, was .00488 against .00488 and .00485 found now. The second-order term of the former specimen had the abnormal sign.

Cobalt. This crystallizes in the hexagonal system, so that measurements in two orientations are necessary for complete characterization. I was fortunate to obtain from Dr. Bozorth of the Bell Telephone Laboratories single-crystal specimens in the two orientations, parallel and perpendicular to the hexagonal axis. The original source of the material was the Katanga Company. The analysis of this particular lot was not taken, but a comparable batch gave Fe 0.05% and Cu 0.01%. It was heat treated in pure hydrogen just below the melting point. Both of these specimens were unusually smooth, without

definite hysteresis. This is by far the most satisfactory material of any described to this point. The deviation of the volume compression from linearity is definite and in the normal direction. The linear compressions in the two directions are approximately the same, which would be expected since the crystal is a close packed structure of *spheres*. The former[13] volume compression at 10,000 corrected for the 1940 iron, and measured in the range to 12,000 on a polycrystalline aggregate, was .00528 against .00504 now.

Nickel. This material in single-crystal form, I also owe to the courtesy of Dr. Bozorth. Since it is cubic, measurements in a single direction suffice. The original source of the material was the International Nickel Company. The analysis was not stated, but the purity is thought to be comparable to that of a single crystal of iron, also from Dr. Bozorth, the analysis of which will be stated later. Like cobalt it had been heat treated in hydrogen near the melting point. A considerable number of measurements were made on this specimen since it was evident from the first that there was something peculiar about it. It was first pressure seasoned by two applications of 30,000. Four sets of measurements to 30,000 were then made in the former inadequately sensitive apparatus, then a measurement in the final apparatus. No consistency was obtained. The nickel was then annealed by heating to a red heat in an evacuated tube for one hour and cooled with the furnace. Two measurements to 30,000 were then made with the final apparatus, then three seasoning applications were made of 30,000 without measurement, and then the final measurement to 30,000. All the measurements with the final apparatus indicated the same thing, a break in direction, or a transition of the second kind. The parameters of this second order transition changed with successive applications of pressure, the pressure at which the discontinuity occurred fluctuating between 10,000 and 20,000 kg/cm², and the amount of discontinuity also fluctuating. On the final measurements the magnitude of the discontinuity reached its largest value. The experimental points of the last run are shown in Figure 3. These correspond to the values given in Table I. The break at 10,600 amounts to a discontinuity in $1/v_0\left(\frac{\partial v}{\partial p}\right)_\tau$ of 6.9×10^{-8} (kg/cm² units) in the direction of an *increased* compressibility at higher pressure. The effect of pressure on the electrical resistance of nickel should obviously be studied in the same range. Previous measurements[14] have been made in the range to 12,000 on two polycrystalline specimens of presumably inferior purity. The corrected compressions at 10,000 were .00518 and .00514 against .00479 above. The differ-

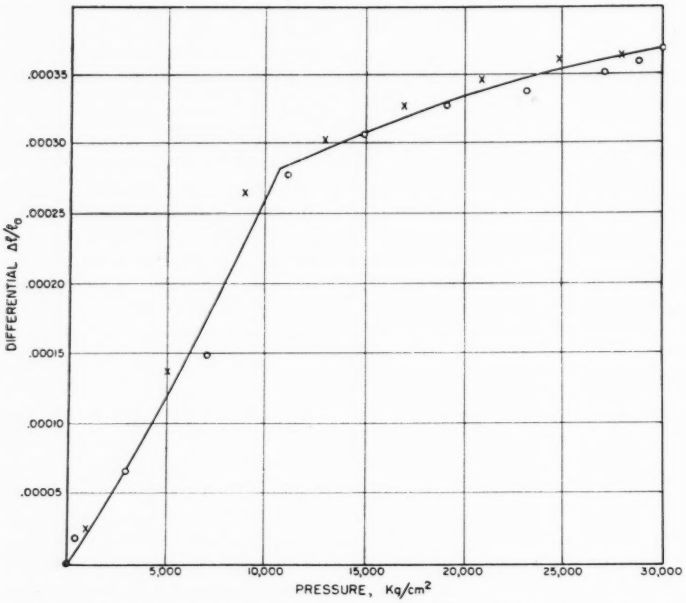

FIGURE 3. The experimental values for the differential change of length of nickel. The circles are for increasing pressure and the crosses for decreasing.

ence is extreme and doubtless connected with the second-order transition; it has been my experience that such a transition may be suppressed if the specimen is subject to constraint.

Palladium. This was obtained on loan from Baker and Company in the same batch as the iridium, rhodium, and platinum already described. It was worked from a casting and drawn to diameter. The individual points lie rather smoothly, without probable hysteresis. There is a definite cusp, or transition of the second kind, at 16,500 kg/cm², where the volume compressibility, $1/v_0 \left(\frac{\partial v}{\partial p}\right)_\tau$, has a discontinuity of 6.9×10^{-8}, the compressibility being *greater* at higher pressures. The amount of the discontinuity is by chance the same as for nickel and in the same direction. The electrical resistance of palladium has not yet been measured in this pressure range. The previous[15] corrected compression at 10,000 of a specimen in wire form measured

over the 12,000 range was .00507, exactly the same as the present value.

Gold. This was "highest purity" material obtained a number of years ago from Baker and Company. Gold from the same stock has been used in many of my calibrations of piezometers to 50,000 and 100,000. It was formed for the present measurements by cold extrusion from 0.25 inch diameter to 0.20 inch, annealed at red heat, pressure-seasoned twice to 30,000, and measured once in the preliminary piezometer to 30,000 and again in the final piezometer. The points lay smoothly but with a consistent hysteresis not expected for this soft material. It was reannealed at a red heat, pressure-seasoned by three applications of 30,000, and again measured in the final piezometer. The previous pattern repeated, the hysteresis being in the abnormal direction, and in amount nearly the same as before. The width of the hysteresis loop was equal to 0.48 per cent of the maximum distortion. The mean deviation from the smooth curve given in the table is the deviation from the branches of the loop, not from the mean curve through the center of the loop. It will be noticed that the individual points lie with unusual smoothness; the hysteresis for this specimen is undoubtedly real. The deviation of volume compression from linearity in pressure is in the normal direction. The previous[16] corrected compression at 10,000 for the 12,000 range was .00556 against .00558 now.

Columbium. This was obtained from the Fansteel Company in 1946, described simply as "special high purity material." It had been annealed by them. It was pressure seasoned to 30,000 twice, then measured once in the preliminary piezometer and again in the final piezometer to 30,000. The pattern of hysteresis was so distinctive that it was annealed again by heating to 900° C. in vacuum, pressure-seasoned three times to 30,000 and again measured in the final piezometer. The pattern was again much the same as before, with a hysteresis loop not of the conventional shape, but the major part of the loop was below 15,000 kg/cm^2, and above that the loop dragged out in a rapidly narrowing tail. The narrowing at the high pressure end was somewhat more pronounced after the second annealing and seasoning. The hysteresis pattern is so definite and characteristic that the results for both increasing and decreasing pressure are reproduced in the table. It will be noticed that the hysteresis is in the abnormal direction. The deviation from linearity is in the normal direction. The smoothness of the individual points, which is calculated from the individual branches of the loop, is quite exceptional, by far the best recorded up to this point. The previous[17]

corrected compression at 10,000 for the 12,000 range measured on a specimen obtained from Fansteel in approximately 1929, was .00559, which is between the two values .00569 and .00556 now found for the two branches of the loop.

Iron. Measurements were made on three different specimens. The first was American Ingot iron from the same bar as that used in all my calibrations and for which the absolute compression has been previously determined by another method.[3] The particular specimen used here had been subjected to two measurements to 30,000 kg/cm^2 before the final measurements recorded in the table. These recorded values are identical with the values of the absolute compression already given, the various small corrections to the piezometer being determined from these measurements so as to give identity. The second specimen was a single crystal which I owe to the courtesy of Dr. R. M. Bozorth. It is from the same batch as that for which other constants have been published by Dr. Bozorth[18] and had the analysis: Ni 0.008%, Si 0.002%, C 0.008%, S 0.001%, Co, Cr, Mo, Mn, O less than 0.001%, Cu less than 0.005%. It was subjected to two preliminary applications of 30,000 before the final measurements. The compression measurements on this single crystal gave results completely indistinguishable from those with the American Ingot iron, so that it is not tabulated separately. The third specimen was a "hydrogen purified carbonyl" iron which I owe to the courtesy of Dr. R. F. Mehl of the Pittsburgh Institute of Technology. It had been heat-treated in hydrogen for 500 hours at 1200° C. A typical analysis, not on the identical specimen, was Cu and Mn about 0.01%, with spectroscopic traces of Si, Mn, Sn, Ni and Al. The preliminary seasoning of this was not as elaborate as for the other two specimens, consisting only of a single application of 10,000 kg/cm^2. The compression under 30,000 is about 0.5 per cent less than for the two other specimens. None of these three specimens showed the slightest indication of hysteresis. The exceptional smoothness of the results is to be noted. It has already been commented on how fortunate it is that the material of which the piezometer is constructed is one which shows no irregularities under pressure. The deviation from linearity is in the normal direction and about the same in magnitude as that of gold.

Copper. This was electrolytic copper of 99.999 per cent purity, which I owe to the courtesy of Dr. A. B. Greniger a number of years ago, at that time a member of the Harvard Department of Metallurgy. It was subjected to six series of measurements to 30,000, being used in the preliminary improvement of the apparatus. Only the last

measurement was with the apparatus in the final form, but with the next to the last the final form was so nearly attained that nearly full significance can be attached to the results. This specimen of copper never settled down to smooth single-valued variation with pressure, but a definite hysteresis in the normal direction persisted, the width of the loop being very nearly the same on the last two runs. The loop was not completely closed at the low pressure end. In the table the mean points are shown, for the mid-curve of the loop, but the deviations from smoothness of the single readings (0.14%) are deviations from the branches of the loop. The width of the loop was 1.4 per cent of the maximum distortion. The deviation from linearity is in the normal direction. The former[19] corrected compression at 10,000 for less pure Cu in the 12,000 range was .00700 against .00696 now.

Titanium. This was a piece of the recently produced "ductile" titanium, which I owe to the courtesy of the Remington Arms Company. It presumably is of materially higher purity than the specimen formerly measured in 1929.[19a] The specimen was turned to dimensions from a rod 0.25 inch in diameter, presumably a drawn rod. Titanium is known to crystallize in the hexagonal system, so that a full characterization of the compression properties would demand two orientations from a single crystal. The axial ratio for this substance is given by Wyckoff as 1.60, which is so close to that for the hexagonal close packed arrangement of spheres, 1.63, that it is probable that the compressibility is nearly equal in the crystallographically different directions. The irregularity of the results for this material was somewhat greater than usual and great enough to obscure any hysteresis. An adequate explanation is failure of the compressibility to be completely isotropic because of the hexagonal crystal system. The former compression at 10,000 was .00808 against .00900 found now. The unusually large difference is doubtless due to inadequate purity of the former specimen.

Silver. This was Baker and Company's purest silver obtained from them a number of years ago. It had been subjected to pressure several years ago in the course of exploratory measurements, and again in a preliminary apparatus before the final measurements recorded in the table. The smoothness of the results is not notable, but there was no consistent hysteresis. The deviations from linearity are unsymmetrical, the greatest curvature being in the upper half of the pressure range instead of the lower half, as is more usual when there is any distinction at all. The previous[20] corrected compression at 10,000 on another specimen measured in the 12,000 range was .00946 against .00938 now.

Silicon. I owe this material to the courtesy of Dr. W. Shockley of the Bell Telephone Laboratories, who in turn obtained it as highly purified material from the laboratories of the Dupont Company. It was subjected to several preliminary applications of 25,000 kg/cm^2 to season. This material probably exhibits some slight hysteresis, but it is mostly swamped by the other irregularities, and the deviations from smoothness have been taken from the mean curve. There are no previous measurements on specimens of sufficient purity to justify comparison.

Beryllium. Measurements were made on only a single specimen. This was a piece of a single crystal, the length being parallel to the cleavage plane (perpendicular to the hexagonal axis), and was the identical specimen as that measured formerly[21] in a narrower pressure range. Unfortunately the specimen in the perpendicular orientation had been broken and no new specimen was available, so that these results are only partial. The specimen was subjected to at least one preliminary application of 30,000. The pattern of deviation from a smooth curve shows definite hysteresis, the width of the loop being about 0.8 per cent of the maximum distortion. However, the deviations were scattered rather less consistently than usual, and the deviation from a smooth curve given in the table (0.41%) is the deviation from the mid-curve of the loop, not the deviation from the branches of the loop separately. The former corrected compression at 10,000 for the identical specimen, measured in the 12,000 range, was .00270 against .00309. The difference is larger than usual; if genuine, it indicates an unusually large effect of increasing the pressure range.

Germanium. This, which was high-purity material of recent manufacture, I also owe to the courtesy of Dr. W. Shockley. It was seasoned by several preliminary applications of 25,000 kg/cm^2. There is undoubtedly some hysteresis in the normal direction, but the irregularities pretty much obscured it, so that no attempt has been made to estimate the width of the hysteresis loop, and the deviation from smoothness reported in the table is the deviation from the mean curve. The previous[22] value for the corrected compression at 10,000 measured on a different specimen in the 12,000 range, was .0136 against .0124 now. The difference is presumably to be ascribed to improved purity in the material.

Aluminum. This was high-purity material obtained a number of years ago from the Aluminum Company of America, through the courtesy of Dr. Greninger. The analysis was: Al 99.966, Cu .022, Fe

.005, Si .007. It had been subjected to several previous applications of pressure in the course of exploratory measurements some years before these measurements. There was some normal hysteresis discernible in the deviation, but the pattern was not especially consistent and the deviations from smoothness given in the table are calculated from the mean curve. The width of the loop was of the order of 0.5 per cent of the maximum distortion. The previous[23] corrected compression at 10,000 measured on another sample in the 12,000 range was .01290 against .01312 now.

Antimony. The origin of the material was Kahlbaum's high purity metal of the early 1920's. This had been cast into single-crystal form and a selection was made of the pieces still extant. Unfortunately the parallel orientation formerly measured had been fractured and there was none to replace it, the best orientation available being with the length at 8° to the axis. Measurements were made on two specimens, one of the 8° orientation and the other in the 90° orientation (axis perpendicular to the length). From the measured linear compressions in the perpendicular and 8° orientations the compression in the parallel orientation may be readily calculated if it is assumed that the specimen acts like a simple linear element with thickness vanishingly small compared with the length. The formula so obtained is

$$\kappa_{\parallel} = \kappa_{8^\circ} + (\kappa_{8^\circ} - \kappa_{\perp}) \tan^2 8^\circ$$

and this formula was used in computing $(\Delta l/l_0)_{\parallel}$ as given in the table. Actually, however, the specimen is not a linear element, but the thickness is about a quarter of the length. There is accordingly a change of angle between the ends and the length under the action of pressure, causing the specimen to shear over in such a way as to give too small an apparent compression. This effect is probably negligibly small in the case above, the correction from the 8° to the parallel orientation being small as shown in the table, but for higher orientations the error may be by no means negligible. A set of measurements was actually made on the 49° orientation, and this yielded computed values for the parallel compression smaller by about 15 per cent than the values of the table.

The perpendicular orientation displayed no hysteresis pattern. The 8° orientation, on the other hand, showed a well marked loop with width 1.3 per cent of the maximum distortion. The average deviation from a smooth curve given in the table, 0.48 per cent, was calculated from the mean curve of the loop; it would have been materially less if calculated from the separate branches. The pre-

vious[24] corrected linear compression at 10,000 kg/cm², measured on similar but not identical material in the 12,000 range, was .00483 for the perpendicular orientation and .01439 parallel, against .00468 and .01498 (the latter calculated) found now.

It is to be noted that the falling off of compressibility with increasing pressure is much greater for the parallel than for the perpendicular orientation. This agrees qualitatively with the former results, the former second degree term for the parallel orientation being five times as great as for the perpendicular direction.

Zinc. New specimens were cut from the remaining stock of single crystal material supplied me by Professor Tyndall in 1935[25] of zinc of unusually high purity, and handled with special care to avoid the strains to which single crystal zinc is particularly susceptible. The compressibility of zinc exhibits a high degree of non-isotropy, the initial compressibility in the parallel orientation (cleavage plane perpendicular to the length) being 8.5 times as great as in the perpendicular orientation. Two sets of measurements were made on the parallel specimen. The pressure range of the first set was only 15,000 kg/cm², higher pressures producing shortening beyond the range of the lever. The specimen was then cut in two and a regular run made to 30,000. The compression at 15,000 on this run agreed within 0.3 per cent with the first run. This orientation showed hysteresis, the width of the loop being 1.6 per cent of the maximum distortion. The nature of the loop and the nature of the irregularities was much like that formerly found[25] in the lower range of 12,000.

The perpendicular orientation (cleavage plane parallel to the length) was not so simple, and more measurements were made on it. Two specimens were first cut from the same original crystal and subjected to the conventional seasoning treatment. Measurement to 30,000 on the two specimens both gave marked cusps or transitions of the second kind, but the character of the deviations from linearity were strikingly different, one specimen giving an unusually large increase of compressibility with pressure, while the other was normal. Repetition on one specimen again gave a pronounced cusp, but now situated at 10,000 instead of at 20,000 kg/cm². Another specimen from another crystal was now prepared with unusual care, and measured immediately in the virgin condition, without the customary seasoning. A second application of 30,000 was then made, and then two sets of measurements during the third and fourth application of 30,000. This specimen showed no such cusps as the others and the results were in fairly close agreement, the extreme difference between different determinations of the linear compression under 30,000 being 0.25

per cent. Furthermore, the absolute values of the compression with this specimen varied from 2 to 6 per cent less than with the other two specimens. This is the direction in which former experience has shown that internal strains act. For the final result, the mean of the three measurements on the last specimen was used, discarding those on the two others.

These experiments on zinc are instructive in showing that in at least some cases irregularity, non-reproducibility, and discontinuities (transitions of higher orders) may be the result of internal strains and do not necessarily imply impurity.

The former[25] corrected results obtained in the 12,000 range for the linear compression at 10,000 were .01277 and .00154 for the perpendicular and parallel orientations respectively against .01277 (identical) and .00151 found now.

Thorium. This was the identical specimen which was formerly measured, obtained in 1926 from Dr. Rentschler of the Westinghouse Lamp Company. There was no certain hysteresis pattern; the irregularities were mostly confined between 10,000 and 20,000. The former corrected compression at 10,000 obtained from measurements over the 12,000 range was 0.0170 against 0.0173 now.

Tin. The same specimens were used that were formerly measured in the range to 12,000. Neither orientation showed a distinctive hysteresis pattern, and the irregularity was practically the same in the two directions. The previous corrected linear compression at 10,000 was 0.00563 for the perpendicular direction and 0.0632 parallel against .00561 and .00621 now.

Tellurium. The identical specimens were used as in the former[28] measurements. In the parallel orientation there was definitely hysteresis, the width of the loop being 1.5 per cent of the maximum distortion. In the perpendicular direction the hysteresis was slight. The irregularity, measured from the mean curve, was nearly the same for the two orientations. The previous linear compressions at 10,000 in the perpendicular and parallel directions were 0.0222 and − 0.00315 respectively, against 0.00214 and − 0.00390 found now. Especially to be noticed is the negative linear compressibility of this element along the trigonal axis. The deviation from linearity in the pressure for this orientation is also noteworthy.

Alloys and Intermetallic Compounds

Carboloy No. 999. This grade of carboloy is the hardest made by the Carboloy Company, and contains the minimum amount of binder.

It is the material which I have used for the pistons of my piezometers for reaching 100,000 kg/cm², the plastic deformation under simple compression being a minimum. There was probably some slight normal hysteresis, but it was pretty well masked by the general irregularity. There is a slight deviation from linearity of the volume compression, which is 44 per cent of that of iron. Young's modulus for carboloy is about 33 per cent of that of iron. The volume compression was calculated, as always, under the assumption of isotropy, which is perhaps somewhat questionable in view of the method of formation from the powder.

Carboloy No. 905. This is the next hardest grade after No. 999, with somewhat more binder. When used as a piston it shows distinctly more plastic flow. The compression is somewhat greater than that of No. 999 as might be expected from the greater amount of binder (cobalt). A somewhat greater amount of normal hysteresis is discernible than for Grade 999. There is a very slight deviation from linearity of the volume compression in the abnormal direction. There is no reason for supposing that this may not be genuine in view of its physical composition as a sintered product.

Nirex. This alloy is the same as that from which the slide wire of the piezometer is made; its composition has already been given. Measurements were made of the compression in order to determine a small correction in converting piezometer readings to change of length. The specimen measured was from an annealed rod 7/32 inch in diameter furnished by Driver Harris in response to my special request. The lever piezometer was not adapted to measuring the compression of the wire actually used in the piezometer. The specimen was seasoned by a preliminary application of 25,000. There was slight hysteresis in the normal direction, mostly masked by the irregularities. The compression is slightly less than that of iron, but so near to it that the resulting correction is almost negligible.

Stainless Steel "H 26." This stainless steel has the composition: C .094, Mn .36, P .023, S .022, Si .35, Cr 12.26, Ni .46, Mo .50, Cu N.D. I owe it to the courtesy of Dr. A. L. Feild of the Rustless Iron and Steel Corporation, from whom I obtained it a number of years ago. It is the same steel for which data on the effect of pressure in modifying the plasticity have already been published.[29] There is definite hysteresis in the normal direction, the width of the loop being 0.16 per cent of the maximum distortion. The loop is open at the lower end. The deviations from smoothness given in the table are deviations from the separate branches of the loop. The mean com-

pression of this grade of stainless steel is almost exactly the same as that of pure iron, but the hysteresis characteristics are quite different. The deviation from linearity is in the normal direction.

Martensite. From the metallographical point of view there is considerable interest in finding whether martensite experiences irreversible changes under the action of hydrostatic pressure. Dr. B. L. Averbach of the Department of Metallurgy of the Massachusetts Institute of Technology furnished me with four different specimens of martensite of different thermal treatments. After exposure to pressure these were examined by him by a new method of great sensitiveness to find whether there had been permanent alterations in the dimensions. Other specimens from the same batch I measured for compression in my conventional way. The specimens were all made from the same 1.1 carbon steel. They were all quenched from 1450° F. into iced brine, a treatment which is said to ensure practically 100 per cent martensite in the end product. Four different further treatments were then given to the martensite as thus prepared. The first was the null treatment. The second was refrigerated by holding at − 321° F. for one hour. The third was tempered by holding at + 300° F. for one hour, and the fourth was refrigerated as above, followed by a tempering as above. These four specimens are designated as: Q, QR, QT, QRT. The results for only Q and QRT are reproduced in full in the table. These specimens were measured without preliminary application of pressure in order to reveal any irreversible effects of hydrostatic pressure. None of them showed any measurable permanent change of length, a result which was independently confirmed by Dr. Averbach, and which I believe he intends to make the subject of a special communication elsewhere. All four specimens showed marked hysteresis in the normal direction, far beyond any possible error or irregularity. The deviations from smoothness given in the table are deviations from the two branches of the loop. It will be seen that the smoothness compares favorably with the best of the previous substances, pure iron. The results for specimens Q and QR are practically identical. If anything, the loop for QR is a trifle wider and the absolute compression a trifle less. The width of the loop is approximately 1 per cent of the maximum distortion. The specimen QT is markedly different, the hysteresis loop having narrowed to one-half the width. This process is carried a little further in QRT, the loop being further narrowed, and also altered in shape, the two branches of the loop coalescing up to about 7,000 kg/cm².

It is evident that as far as behavior under hydrostatic pressure

goes, tempering has a greater effect than refrigerating. The hysteresis is not surprising in view of the fact that martensite is composed of tetragonal crystals, so that under hydrostatic pressure the individual crystals do not deform uniformly in every direction, with resultant development of internal strains.

Before the measurements recorded above on Dr. Averbach's martensite measurements were made on a specimen of commercial drill rod (1.25 per cent C.), quenched and drawn in boiling water. The results were similar, except that the hysteresis loop now was about twice as wide as for the specimen "Q" above.

Stainless Steel "H 29." The composition of this was: C 0.058, Mn 0.70, P 0.030, S 0.013, Si 0.85, Cr 18.51, Ni 8.95, Mo ND, Cu 0.20. Otherwise the same remarks[29] apply as to "H 26." There is marked hysteresis and the deviations from smoothness given in the table are deviations from the branches of the loop. The mean curve is not of the conventional simple shape but is gently S shaped. The volume compressions of the table refer to the mean curve. The maximum width of the loop was 1.16 per cent of the maximum distortion.

Cu_3Au. This was a single crystal which I owe to the courtesy of Dr. Sidney Siegel who prepared it in the Research Laboratory of the Westinghouse Company. It was one of a set of crystals for which he determined[30] the variations of the elastic moduli with temperature. It was subjected to several seasoning applications in the course of early unsuccessful attempts at measurement, at one time reaching a maximum of 30,000 with no permanent change of dimensions, before the measurements recorded in Table II. The hysteresis phenomena are complicated and unusual. The mean curve is S shaped; the loop itself has maximum width at 8,000 and again at 20,000 kg/cm^2, amounting to 1.0 per cent of the maximum distortion. The loop constricts itself to a wasplike waist of vanishing width at 15,000. The deviations from smoothness given in the table are deviations from the mean curve. The hysteresis is in the normal direction, but the initial departures from linearity are in the abnormal direction. There are no previous measurements of compressibility for comparison. Dr. Siegel has, however, calculated from the elastic moduli that the cubic compressibility at 20° is 6.3×10^{-6} (kg/cm^2 units) against 6.0 extrapolated to zero from the above. The agreement is good when consideration is given to the fact pointed out by Dr. Siegel that the calculated compressibility is inaccurate because of the unfavorable values of the moduli, S_{11} being nearly equal to $-2S_{12}$.

Au Zn. This was the identical specimen which had been previously[31]

TABLE II

COMPRESSION OF ALLOYS AND INTERMETALLIC COMPOUNDS

Pressure kg/cm²	$\Delta V/V_0$									
	Carboloy No. 999	Carboloy No. 905	Nirex	Stainless Steel H26	Martensite (1.1% C) Q Inc.	Q Dec.	Q.R.T. Inc.	Q.R.T. Dec.	Stainless Steel H 29	Cu_3Au	Au Zn
5,000	.00123	.00126	.00276	.00290	.00293	.00300	.00295	.00295	.00301	.00305	.00402
10,000	.00245	.00250	.00543	.00573	.00579	.00592	.00579	.00582	.00599	.00629	.00786
15,000	.00372	.00379	.00811	.00863	.00870	.00895	.00864	.00870	.00901	.00955	.01157
20,000	.00495	.00506	.01071	.01136	.01154	.01166	.01147	.01148	.01195	.01269	.01506
25,000	.00618	.00636	.01325	.01409	.01435	.01442	.01426	.01423	01482	.01572	.01846
30,000	.00737	.00763	.01573	.01676	.01711		.01689		.01757	.01860	.02168
Average percentage deviation from smooth curve	.066	0.80	0.16	0.02	0.018		0.014		0.05	0.27	0.09

Pressure kg/cm²	$\Delta V/V_0$									
	35% Ni 65% Fe	$Cu_{31}Sn_8$	Cu Zn	Ag_2Al	Cu_5Zn_8	Ag Zn	Ag_5Zn_8	Cu_5Cd_8	Sb Sn	Sb_2Tl_7
5,000	.00453	.00451	.00442	.00491	.00527	.00504	.00525	.00632	.0104	.0141
10,000	.00896	.00880	.00873	.00967	.01020	.00991	.01036	.01224	.0198	.0267
15,000	.01337	.01297	.01298	.01436	.01492	.01473	.01541	.01793	.0288	.0383
20,000	.01759	.01689	.01708	.01886	.01938	.01930	.02026	.02333	.0371	.0491
25,000	.02167	.02066*	.02106	.02315	.02370	.02369	.02494	.02851	.0448	.0590
30,000	.02459	.02475*	.02487	.02721	.02788	.02790	.02944	.03353	.0522	.0682
Deviation from smoothness	0.26	0.20	0.22	0.29	0.32	0.37	0.18	0.22	0.37	0.17

*Cusp at 25.500

measured to 12,000. There is well developed hysteresis in the normal direction. The width of the loop is 1.15 per cent of the maximum distortion. The deviations from smoothness given in the table are the deviations from the branches of the loop. The deviation from linearity, which is in the normal direction, is marked. The previous corrected value of compression at 10,000 was .00731 against .00786 found now. The previous measurements to 12,000 disclosed even more marked hysteresis than the present measurements, the width of the loop being 3.6 per cent of the distortion at 12,000.

"*Alloy 121.*" This was a single crystal of composition 35% Ni and 65% Fe which I owe to the kindness of Dr. R. M. Bozorth of the Bell Telephone Laboratories; it was prepared by Mr. H. J. Williams. There is well developed hysteresis in the normal direction, but the loop is not wide, being only 0.49 per cent of the maximum distortion. The deviation from smoothness given in the table, 0.26%, is the deviation from the mean curve. This deviation is almost entirely accounted for by the width of the loop, all the points except one lying unusually close to the branches of the loop. The deviation from linearity is in the normal direction. It is to be noticed that the absolute compression is about 50 per cent greater than would be calculated from either component separately. This is highly unusual; it is normal for the compressibility of an alloy to be less than that calculated by the rule of mixtures from the components.

$Cu_{31}Sn_8$. This was the identical specimen, No. 4, which was previously[32] measured. In the previous work much variation was found in specimens of the material prepared under closely similar conditions. Four specimens were previously measured with an initial compressibility varying from 8.8 to 11.4×10^{-7}. Of these specimens No. 4 was the one with minimum hysteresis and maximum regularity. There is a marked cusp at 25,000 kg/cm², $\frac{1}{v_0}\left(\frac{\partial v}{\partial p}\right)_\tau$ increasing abruptly by 8.7×10^{-9} (kg/cm² units) at this point. Below this pressure there is a well marked, but narrow, hysteresis loop in the normal direction of maximum width equal to 0.55 per cent of the maximum distortion. The deviation from smoothness given in the table, 0.20 per cent, is the deviation from the mean curve. The previous corrected compression at 10,000 was .00933 against .00896 now. Considering the character of the material the difference is not surprising.

Cu Zn. This was the identical specimen used in previous[33] measurements to 12,000. The seasoning operation was not adequate, however, for the hysteresis, which was in the normal direction, was un-

usually large, and furthermore the loop was not closed at the origin. The width of the loop at the maximum was 1.7 per cent of the maximum distortion, and at the open end at the origin 1.5 per cent. The deviations from smoothness given in the table are deviations from the branches of the loop. The deviation from linearity is in the normal direction, but is not as large as might be expected for a substance of this absolute magnitude of compression. This may be connected with the abnormal and open hysteresis. The former corrected compression at 10,000 was .00879 against .00873 now. In the former measurements over the 12,000 range the hysteresis was much larger than above, the width of the loop being 8.5% of the distortion at 12,000. The irregularities formerly found in the 12,000 range were relatively much larger than found now.

Ag_2Al. This is the identical specimen, No. 1, which was formerly[34] measured at 12,000 kg/cm^2. There is definite hysteresis in the normal direction; the width of the loop is 0.57 per cent of the maximum distortion. The deviations from smoothness given in the table are deviations from the mean curve. Deviation from linearity is normal. The former corrected compression at 10,000 was .00997 against .00967 now. Former measurements were made over an interval of fifteen months and showed considerable secular change in this interval. The initial measurements disclosed a break in the tangent between 5,000 and 6,000; there is now no trace of such a break in the range to 30,000.

Cu_5Zn_8. (Gamma Brass) I owe this to the kindness of Dr. Cyril Smith of the Institute for the Study of Metals of the University of Chicago. The specimen was cut from a larger specimen destined for a study of the effect of hydrostatic pressure on plasticity in tension. The results of this study will be reported elsewhere. There is small hysteresis in the normal direction. The deviations from smoothness given in the table are deviations from the mean curve; the deviation calculated from the branches of the loop is about one-half as great. Deviation from linearity is in the normal direction. The previous[35] corrected compression at 10,000 on another specimen measured over the 12,000 range was .00970 against .01020 now.

$AgZn$. This was the same specimen as previously[36] measured to 12,000. There is definite hysteresis in the normal direction, the width of the loop being 0.87 per cent of the maximum distortion. The deviations from smoothness reported in the table are deviations from the mean curve. Deviation from linearity is in the normal direction. The former corrected compression at 10,000 was .01024 against

.00991 now. The former measurements in the 12,000 range disclosed much greater irregularities than found now. Part of the difference is doubtless due to slow secular changes in the material as well as the difference of pressure range.

Ag_5Zn_8. This was the same specimen as formerly[37] measured to 12,000. There is no certain hysteresis. However, half the total deviation from smoothness was contributed by the two points at 9,000 and 5,000 on decreasing pressure. These deviated from the smooth curve in the direction of normal hysteresis. Deviation from linearity is normal. The former corrected compression at 10,000 was .01072 against .01036 now. The former measurements showed distinct hysteresis, but on the whole the irregularities were much less than for most of this class of substances.

Cu_5Cd_8. This specimen was formerly[38] measured to 12,000. There is no certain hysteresis. It is not at all improbable that there is a cusp with increase of compressibility near 17,000 kg/cm^2. However, this interpretation depends almost entirely on the evidence of one point, so that I have preferred to smooth the results right over the possible cusp. Should the cusp exist, the effect on the actual relative volume would not produce a difference anywhere of more than 0.00020 compared with the figures given in the table. The former corrected compression at 10,000 was .0137 against .0122 now. The difference is larger than usual.

Sb_2Tl_7. This was the same specimen that had been previously[39] measured to 12,000. The hysteresis was not marked and the regularity was on the whole greater than usual. The previous corrected compression at 10,000 was 0.0296 against 0.0267 now In the former range of 12,000 the regularity of the measurements was also greater than usual.

SbSn. The same specimen was used as in the former[40] measurements to 12,000. There was no obvious hysteresis pattern and the results were in no way noteworthy. The former corrected compression at 10,000 was 0.0202 against 0.0198 now. The former measurements in the range to 12,000 were smoother than usual.

Minerals

A. Minerals Crystallizing in the Cubic System

Garnet. This specimen has been previously[41] measured to 12,000. There is small hysteresis in the normal direction; the width of the loop is 0.62 per cent of the maximum distortion. The deviations from

smoothness in the table are deviations from the mean curve. The former corrected compression at 10,000 was 0.00538 against 0.00529 now.

Mg O. This was a water-clear single crystal. It had been previously[42] measured to 12,000. There is distinct hysteresis in the normal direction; the width of the loop is 0.89 per cent of the maximum distortion. The deviation from smoothness given in the table, 0.18 per cent, is the deviation from the mean curve. The points lie with unusual smoothness on the branches of the loop, and if the deviations had been calculated from the two branches instead of the mean, a smoothness equal to that of the best of the former specimens would have been found. The former corrected compression at 10,000 was .00579 against .00571 now. Various small irregularities were formerly found in the range to 12,000 which were ascribed to a failure of a "perfect state of ease." These effects are here diminished by seasoning through a wider pressure range, which seems natural.

Magnetite. This was the larger of two pieces formerly[43] measured to 12,000. There is perhaps just perceptible hysteresis in the normal direction, but it is too small to attempt to estimate numerically. There is a cusp at 22,500 kg/cm² with increase of $-\frac{1}{v_0}\left(\frac{\partial v}{\partial p}\right)_\tau$ by 2.8×10^{-8} (kg/cm² units). The former corrected compression at 10,000, measured on two pieces stacked together, was .00532 against .00564 now.

Andradite. This has been previously[41] measured to 12,000. There is a cusp at 22,500 with increase of $-\frac{1}{v_0}\left(\frac{\partial v}{\partial p}\right)_\tau$ by 1.09×10^{-7} (kg/cm² units), an unusually large change, which amounts to about one sixth of the total $\frac{1}{v_0}\left(\frac{\partial v}{\partial p}\right)_\tau$. The existence of the cusp was checked by repetition of the measurements both with increasing and decreasing pressure over the region of the cusp. Furthermore, there is hysteresis in the normal direction, the width of the loop amounting to 0.66 per cent of the total distortion. On repetition the points fell on the same loop as with the first measurement, thus checking the genuineness of the hysteresis and the adequacy of the seasoning. The previous corrected compression at 10,000 was .00653 against .00636 now.

Pyrite. This was the second of two specimens which had been previously[43] measured to 12,000. There is hysteresis somewhat confused by the irregularity of the points. The width of the loop is of

TABLE III

COMPRESSION OF CUBIC MINERALS

Pressure kg/cm²	$\Delta V/V_0$								
	Garnet	Mg O	Magnetite	Andradite	Pyrite	Cobaltite	Fluorite	Li F	Galena, PbS
5,000	.00272	.00290	.00286	.00325	.00328	.00353‡	.00585	.00712	.00936
10,000	.00538	.00571	.00564	.00636	.00645	.00702‡	.01147	.01406	.01792
15,000	.00807	.00859	.00845	.00947	.00963	.01087§	.01695	.02068	.02602
20,000	.01071	.01139	.01118*	.01248†	.01282	.01444§	.02213	.02696	.03363
25,000	.01333	.01410	.01394*	.01542†	.01575	.01753	.02735	.03302	.04074
30,000	.01588	.01674	.01670	.01852	.01869	.02050	.03234	.03861	
Average Percentage Deviation from Smooth Curve	0.23	0.18	0.16	0.35	0.27	0.24	0.22	0.41	0.94

*Cusp at 22,500 †Cusp at 22,500 ‡Cusp at 9,500 §Cusp at 18,500

the order of 0.50 per cent of the maximum distortion. The deviations from a smooth curve given in the table are deviations from the mean curve. The previously measured corrected compression of this specimen at 10,000 was .00662 against .00645 now.

Cobaltite. This had been previously[43] measured to 12,000. There are two cusps. At the lower, at 9,500 kg/cm^2, $-\frac{1}{v_0}\left(\frac{\partial v}{\partial p}\right)_\tau$ increases discontinuously by 6.8×10^{-8} (kg/cm^2 units), and at the second, at 18,500, it decreases discontinuously by 1.12×10^{-7}. Between the two cusps the readings with increasing and decreasing pressure differ by 1.39 per cent of the maximum distortion. The difference between the increasing and decreasing readings is in the direction to correspond to a normal hysteresis. There is not, however, a proper loop, but the difference is nearly constant over the range. The deviations from smoothness given in the table are calculated on the mean curve. The previous corrected compression at 10,000 was .00739 against .00702 now. No cusp was previously found; this may well be an effect of the difference of range.

Fluorite. This was previously[43] measured to 12,000. Any hysteresis is somewhat obscured by the general irregularity of the points. What hysteresis there is, is in the normal direction, and the width of the loop is of the order of 0.4 per cent of the maximum distortion. The deviations from smoothness given in the table are calculated from the mean curve. The previous corrected compression at 10,000 was .01148 against .01147 now. The agreement is fortuitous.

LiF. This was a water-clear single crystal prepared in this laboratory a number of years ago by Dr. E. G. Schneider, and was the same specimen that was previously[44] measured in the 12,000 range. There was no definite hysteresis. The previous corrected compression at 10,000 was 0.0143 against 0.0141 now.

Galena. (*PbS*). This was the same specimen as previously[43] measured to 12,000. Galena has already been found[45] to have a transition in the neighborhood of 25,000. This transition was again found here, so that the measurements above 25,000 were without special significance. This transition is apparently one of those which run without drastic rearrangement of the lattice, the original lattice being recovered after the reverse transition runs. This was suggested by there being no permanent change of length, by the approximate coincidence of the pressure points with increasing and decreasing pressure after the occurrence of the transition, and by the unaltered

appearance of the specimen, in which the reflection pattern was unusually prominently developed. As a further check, the specimen was destroyed after the measurements by cleaving it, to find whether there had in fact been any change in the actual cleavage. It was found that in fact the location of the cleavage plane was unchanged, thus checking the above characterization of the transition. But in making the cleavage, a small inclusion of some white foreign substance was found, which was entirely unsuspected from the unusually sound appearance of the exterior. This inclusion doubtless introduces some error, probably small, into the absolute value for the compression, and more importantly is probably responsible for the unusually large irregularity in the results. Any conventional hysteresis was masked by the irregularities. The former value for the corrected compression at 10,000 was 0.0178 against 0.0179 now. In the former measurements the specimen was presumably virgin, not having experienced the transition. At least it had not experienced it in the laboratory, and the pressure of the transition would demand a depth of origin in the earth such that it probably had not occurred in nature.

B. Non-Cubic Minerals

Al_2O_3 (*Sapphire*). This was new synthetic material which I owe to the courtesy of the Linde Air Products Co. The specimens were cut from single rods, grown by their well-known method. Two orientations were measured, one with the c axis at 90° to the length, and the other with the c axis at 10° to the length. It would have been desirable if the 0° orientation could have been measured, but low orientations do not often occur, and considerable search was necessary to find a suitable specimen with orientation as low as 10°. In addition to the control on orientation, the specimens were selected for freedom from internal flaws, which usually take the form of minute bubbles. The rods were subjected to examination with a low-power microscope and specimens found which appeared almost completely free from imperfections. After selection, they were centerless ground in order that the external surface should be cylindrical.

Six sets of measurements were made on the 90° orientation and two on the 10°—more than on most substances. The results given in the table are means of all the runs, each run being weighted inversely according to the average deviation of its single points from a smooth curve. The material showed no tendency to settle down to a smooth final behavior, but the irregularities persisted through all the runs. This is no doubt a consequence of imperfect homogeneity. It has already been found[46] that the mechanical strength of this material is subject to wide and capricious variation. Although the former

material was not as carefully selected as this and complete freedom from visual flaws was not attained, there is no reason to think that complete freedom from flaws of every scale was attained with the present specimens.

It will be noticed that the linear compression is very nearly the same in the two orientations. The formulas are well known for calculating the compression in the 0° orientation from the compressions at 90° and 10°. The correction from 10° to 0° is very small, being at most unity in the next place of decimals beyond the last listed in the table. From the linear compressions at 90° and 0° the volume compression was computed.

The deviations from linearity are small and in the normal direction. Within experimental error, the linear compression in the two orientations was a quadratic function of pressure.

Al_2O_3 has been previously[47] measured to 12,000. The former specimens were cut from a large boule which was unusually free from the large internal strains which make nearly all boules fracture spontaneously when cut. The former specimen showed marked anomalies below 12,000. In the 0° orientation there were marked cusps at room temperature and 75°, and in the 90° orientation a less well marked cusp at 75°. These small effects are with high probability the results of small internal strains. The absolute compression found before was not greatly different from that found now. The linear compression at 10,000 kg/cm^2 found formerly for the 0° orientation was 0.00111 against 0.00118 found now, and for the 90° orientation 0.00104 found formerly against 0.00119 found now. The present results, because of the freedom from marked anomalies, are certainly to be preferred to the former values as being closer to the probable values for the perfect Al_2O_3 lattice.

Beryl. This has been previously[41] measured to 12,000 in the parallel and perpendicular orientations. There is definite hysteresis in the normal direction for both orientations, the width of the loop being 1.2 per cent of the total distortion for the parallel orientation, and 1.4 per cent perpendicular. The individual points lie with great smoothness on the two branches of the loops, the deviations from smoothness given in the table are the deviations from the mean curve; the deviations from the branches of the loop could be about one quarter as much. The corrected changes of length at 10,000 formerly found were 0.00202 and 0.00161 for the parallel and perpendicular orientation respectively, against 0.00199 and 0.00155 found now.

Note the abnormal increase of compressibility in the perpendicular orientation.

Topaz. This crystallizes in the orthorhombic system, so that three specimens at right angles to each other are required. The same specimens were used that had been previously[41] measured to 12,000. All three orientations showed a cusp at 26,000 kg/cm^2 with discontinuous *decrease* of linear compressibility, $-\frac{1}{l_0}\left(\frac{\partial l}{\partial p}\right)_\tau$. This discontinuous decrease was 1.55×10^{-8} for the A orientation, 1.68×10^{-8} for the B, and 1.96×10^{-8} for the C. It could not be maintained, I think, that these differences are significant, and that the discontinuity is not really the same within experimental error for the three orientations. It is to be remarked that the state of affairs is here entirely unlike that of $NiSO_4$ $6H_2O$, for example, in which there is a very marked cusp in one direction but none at right angles to it.[4]

Below the cusp, the A and C orientations show hysteresis in the normal direction which is doubtless beyond experimental error, but the B orientation shows nothing which is not masked by the irregularity of the points. The loops for the A and C orientations are closed at the origin, but open at the cusp end. The maximum width of the loops was 0.75 and 0.50 per cent of the total distortion respectively. The deviation from smoothness given in the table is in all cases the deviation from the mean curve.

The former corrected values for the linear compression at 10,000 kg/cm^2 for the A, B, and C orientations are 0.00211, 0.00145, and 0.00228, respectively, against the former values 0.00210, 0.00144, and 0.00217. It is to be considered whether the alteration in the value for C is the result of the greater pressure range and a permanent change on passing through the cusp.

Spodumene. This mineral has been previously[41] measured to 12,000. It crystallizes in the monoclinic system, so that four orientations are required to completely determine the effect of hydrostatic pressure. The *b* and the *Y* orientations both show hysteresis in the normal direction, but the loop is so obscured by the irregularity that I did not think it worth while to attempt to estimate its width. In the *c* orientation there is no evident hysteresis, and the points are of an unusual regularity. In the *a* orientation the loop width is 0.8 per cent of the maximum distortion. The deviation of the individual points from the branches of the loop is 0.09 per cent, as against 0.37 per cent when measured from the mean curve.

In calculating the volume change given in the table it was assumed that this could be computed with sufficient precision from the *b*, *c*, and *Y* orientation by the formulas applicable to orthorhombic crystals. The corrected linear compressions at 10,000 kg/cm^2 formerly found for

the *a*, *b*, *c*, and *Y* orientations were 0.00177, 0.00242, 0.00197, and 0.00239 respectively against 0.00176, 0.00252, 0.00189, and 0.00225 found now. Formerly the *Y* orientation showed the greatest deviation from linearity (in the normal direction); now it is the *b* orientation.

Tourmaline. The same two specimens of black tourmaline were used as in the former[41] measurements to 12,000; these were parallel and perpendicular to the trigonal axis. There were small abnormalities in the behavior of this material in both orientations. In the parallel orientation there is no conventional hysteresis, but a literal acceptance of the irregularities indicates a saw-tooth pattern in the deviations from a smooth curve, there being four episodes between atmospheric pressure and 30,000. The amplitude of these excursions is small, however, the average deviation from the smooth curve drawn through the midst of the experimental points being only 0.6 per cent. In the perpendicular orientation there is definite hysteresis, the width of the loop being 2.3 per cent of the maximum distortion. The individual points, unlike the parallel orientation, lie smoothly on one or the other branch of the loop, with a mean deviation from the branches of the loop of 0.18 per cent, whereas the average deviation from the mean curve through the loop is 0.6 per cent. The shape of the loop differs somewhat from the canonical, the maximum width of the loop being near 20,000, with a drawn-out tail at the low-pressure end.

The former corrected compressions at 10,000 for the parallel and perpendicular orientation were 0.00465 and 0.00158 respectively against 0.00484 and 0.00185 found now.

Apatite. This crystallizes in the hexagonal system, so that two orientations are necessary. The same parallel and perpendicular specimens were measured here that were formerly[41] measured. In the perpendicular direction the hysteresis phenomena are normal, the width of the loop being 0.77 per cent of the maximum distortion. The hysteresis is not well marked above 20,000. In the parallel direction the hysteresis loop is distinctly S-shaped, so that the deviation from linearity is abnormal and cannot be reproduced by a quadratic expression. The width of the loop at the maximum for this orientation is 1.52 per cent of the maximum distortion. The deviations from smoothness given in the table for both orientations are deviations from the mean curves. The former measurements gave for the corrected linear compressions at 10,000 kg/cm^2 for the parallel and perpendicular orientations 0.00241 and 0.00396 against 0.00240 and 0.00398 respectively found now. Both sets of measurements

agree in giving an abnormally small deviation from linearity to the parallel orientation.

Mica. The results for this are only rough. The chief interest in attempting the measurements at all was to know the order of magnitude of the corrections introduced by the compression of the mica insulation in various pieces of my high pressure apparatus. Mica is monoclinic, so that, in principle, specimens should have been measured in four orientations. Because of the very pronounced cleavage it would have been exceedingly difficult to cut and handle all these orientations and I contented myself with measuring the linear compression in a single orientation cut parallel to the main cleavage plane at an undetermined angle in that plane and also the mean volume compression to 40,000 kg/cm^2 in the apparatus described in a previous paper.[48] The precise variety of mica was not known; the specimen was cut from a nugget from the University Museum about 2 cm. in diameter and 1 cm. thick, with a distorted hexagonal cross-section evidently corresponding to the outline of a single crystal. The thin sheets were nearly perfectly transparent, of a light brown cast.

The linear compression measurements on the orientation parallel to the cleavage plane disclosed an unusually well marked cusp at 19,500 kg/cm^2, with an abrupt drop in $-\frac{1}{l_0}\left(\frac{\partial l}{\partial p}\right)_\tau$ of approximately 8×10^{-8}. Below the cusp there is also marked hysteresis in the normal direction, the width of the loop being 2.2 per cent of the maximum distortion.

If it is assumed that the linear compression is approximately the same for all orientations in the cleavage plane, it may be calculated that the linear compressibility perpendicular to the cleavage plane is approximately twice as great as in the plane. This is the direction of variation to be expected.

Celestite. This has been previously[43] measured to 12,000. It belongs to the orthorhombic system, so that three orientations are required. The a orientation shows irregularity and hysteresis below 15,000, but is perfectly smooth above. The b and c orientation show hysteresis in the normal direction, normally distributed over the entire pressure range. The width of the loop for the b orientation was 0.52 per cent of the maximum distortion, and that of the c orientation 0.38 per cent. The deviations from smoothness given in the table are deviations from the mean curve. The former values for the corrected linear compression at 10,000 kg/cm^2 were 0.00596, 0.00425, and 0.00440 for the a, b, and c orientations respectively against 0.00588, 0.00418, and 0.00423 found now. The present

results agree with the former ones in giving the greater departure from linearity (normal direction) to the *b* orientation.

Barite. This is orthorhombic, so that three orientations are required. It has been previously measured[41] to 12,000. Of the former specimens only that in the *A* orientation was available, so that it was necessary to cut new specimens from other crystals. In the cutting some confusion arose with regard to orientation, so that more specimens were measured to 30,000 than would otherwise have been necessary. Six specimens were measured; these comprised the original *A* orientation, the *A*, *B*, and *C* orientations from the same new crystal, described by Professor Frondel to whose kindness I owe it as the best barite crystal he had ever seen, and two other specimens in the *B* orientation from two other crystals. The orientations were checked by Professor Frondel after the measurements. In Table IV the results are shown for the three orientations all cut from the same good new crystal. This showed no hysteresis. The former corrected compressions at 10,000 for the *A*, *B*, and *C* orientations were 0.00461, 0.00630, and 0.00532 respectively against 0.00478, 0.00634, and 0.00498 found now. The new result at 10,000 on the identical former *A* specimen was 0.00465 against 0.00461, thus checking the method. The outstanding differences are therefore to be ascribed to variation of the material from crystal to crystal. The two other *B* specimens from two other crystals gave at 10,000 and 30,000 0.00674 and 0.00656 and 0.01778 and 0.01745 respectively. The extreme variation at any pressure to be ascribed to the material is about 6 per cent. The deviation of the linear compression from linearity in the pressure is about three times as great in the *A* direction as in *C*.

Hanksite. This mineral is described in Dana as belonging to the hexagonal system, with the composition $9Na_2SO_4 . 2Na_2CO_3 . KCl$. The same specimen in the perpendicular orientation was used as in the former[41] measurements to 12,000; the parallel orientation was a new specimen cut from the original crystal. In neither orientation was there marked hysteresis, but the scattering of the points was greater than usual in the parallel orientation. The previous corrected compressions at 10,000 were 0.01040 and 0.00574 for the parallel and perpendicular directions respectively against 0.01020 and 0.00738 now. The discrepancy in the perpendicular direction is not obviously explainable and would suggest a blunder somewhere. There were a few minor flaws in the specimen, but nothing large enough to account for any such difference.

Quartz. The same two specimens were used as in the former[41]

TABLE IV

COMPRESSION OF NON-CUBIC MINERALS

Pressure kg/cm²	Al_2O_3			Beryl			Topaz			
	$\left(\frac{\Delta l}{l_0}\right)_{90°}$	$\left(\frac{\Delta l}{l_0}\right)_{10°}$	$\Delta V/V_0$	$\left(\frac{\Delta l}{l_0}\right)_{\parallel}$	$\left(\frac{\Delta l}{l_0}\right)_{\perp}$	$\frac{\Delta V}{V_0}$	$\left(\frac{\Delta l}{l_0}\right)_A$	$\left(\frac{\Delta l}{l_0}\right)_B$	$\left(\frac{\Delta l}{l_0}\right)_C$	$\frac{\Delta V}{V_0}$
5,000	.00060	.00059	.00178	.00100	.00077	.00254	.00106	.00072	.00108	.00285
10,000	.00119	.00118	.00355	.00199	.00155	.00509	.00210	.00144	.00217	.00570
15,000	.00179	.00179	.00537	.00299	.00242	.00781	.00317	.00218	.00331	.00863
20,000	.00238	.00239	.00704	.00398	.00320	.01033	.00421	.00291	.00443	.01150
25,000	.00297	.00300	.00891	.00496	.00404	.01297	.00525	.00366	.00555	.01439
30,000	.00355	.00360	.01067	.00585	.00486	.01550	.00622*	.00448*	.00658*	.01718
Average Percentage Deviation from Smooth Curve	0.49	0.93		0.25	0.50		0.24	0.31	0.19	

*Cusp at 26,000

Pressure kg/cm²	Spodumene					Tourmaline		
	$\left(\frac{\Delta l}{l_0}\right)_a$	$\left(\frac{\Delta l}{l_0}\right)_b$	$\left(\frac{\Delta l}{l_0}\right)_c$	$\left(\frac{\Delta l}{l_0}\right)_Y$	$\left(\frac{\Delta V}{V_0}\right)$	$\left(\frac{\Delta l}{l_0}\right)_{\parallel}$	$\left(\frac{\Delta l}{l_0}\right)_{\perp}$	$\frac{\Delta V}{V_0}$
5,000	.00088	.00128	.00095	.00114	.00337	.00245	.00094	.00431
10,000	.00176	.00252	.00189	.00225	.00663	.00484	.00185	.00851
15,000	.00265	.00375	.00283	.00338	.00993	.00715	.00273	.01257
20,000	.00353	.00495	.00375	.00448	.01312	.00937	.00359	.01647
25,000	.00442	.00610	.00466	.00557	.01624	.01147	.00444	.02023
30,000	.00529	.00719	.00556	.00663	.01925	.01336	.00525	.02368
Average Percentage Deviation from Smooth Curve	0.37	0.48	0.05	0.46		0.6	0.6	

TABLE IV (Continued)

COMPRESSION OF NON-CUBIC MINERALS

Pressure kg/cm²	Apatite			Mica		Celestite			
	$\left(\frac{\Delta l}{l_0}\right)_{\parallel}$	$\left(\frac{\Delta l}{l_0}\right)_{\perp}$	$\frac{\Delta V}{V_0}$	$\left(\frac{\Delta l}{l_0}\right)_{\text{parallel cleavage}}$	$\frac{\Delta V}{V_0}$	$\left(\frac{\Delta l}{l_0}\right)_a$	$\left(\frac{\Delta l}{l_0}\right)_b$	$\left(\frac{\Delta l}{l_0}\right)_c$	$\frac{\Delta V}{V_0}$
5,000	.00121	.00203	.00525	.0013	.0049	.00296	.00215	.00215	.00725
10,000	.00240	.00398	.01032	.0028	.0092	.00588	.00418	.00423	.01423
15,000	.00362	.00592	.01539	.0042	.0165	.00861	.00612	.00629	.02088
20,000	.00484	.00779	.02028	.0058*	.0227	.01134	.00795	.00825	.02729
25,000	.00603	.00963	.02508	.0070	.0311	.01377	.00973	.01017	.03330
30,000	.00716	.01139	.02964	.0082	.0353	.01623	.01151	.01198	.03920
Average Percentage Deviation from Smooth Curve	0.40	0.39		0.46		0.24	0.20	0.30	

* Cusp at 19.500

Pressure kg/cm²	Barite				Hanksite			Quartz		
	$\left(\frac{\Delta l}{l_0}\right)_a$	$\left(\frac{\Delta l}{l_0}\right)_b$	$\left(\frac{\Delta l}{l_0}\right)_c$	$\frac{\Delta V}{V_0}$	$\left(\frac{\Delta l}{l_0}\right)_{\parallel}$	$\left(\frac{\Delta l}{l_0}\right)_{\perp}$	$\left(\frac{\Delta l}{V_0}\right)$	$\left(\frac{\Delta}{l_0}\right)_{\parallel}$	$\left(\frac{\Delta l}{l_0}\right)_{\perp}$	$\frac{\Delta V}{V_0}$
5,000	.00247	.00323	.00251	.00819	.00523	.00369	.01256	.00334	.00480	.01289
10,000	.00478	.00634	.00498	.01601	.01020	.00738	.02476	.00642	.00909	.02440
15,000	.00696	.00934	.00740	.02351	.01455	.01073	.03558	.00920	.01308	.03495
20,000	.00895	.01222	.00973	.03058	.01843	.01379	.04531	.01170	.01688	.04478
25,000	.01076	.01495	.01204	.03728	.02196	.01662	.05419	.01406	.02056	.05418
30,000	.01243	.01748	.01427	.04354	.02522	.01927	.06241	.01622	.02411	.06308
Average Percentage Deviation from Smooth Curve	0.79	0.39	0.94		1.1	0.30		0.28	0.42	

measurements to 12,000 of 1924–25. Neither orientation showed definite hysteresis. The former corrected compressions at 10,000 for the parallel and perpendicular orientations were respectively 0.00644 and 0.00901 against 0.00642 and 0.00909 now.

Organic Crystals

Finally, results are given for three organic crystals, only one with a complete set of orientations. Many organic crystals are soluble in the ordinary pressure transmitting medium, so that special methods have to be employed. The three measured here do not suffer from this difficulty and were such that they could be easily measured with the apparatus at hand. In general, the absolute values of the compressions of organic substances may be expected to be materially greater than that of the other substances of this paper, and the departure from linearity correspondingly greater.

Sucrose. (Cane Sugar). This crystallizes in the monoclinic system, requiring four compression specimens. The same specimens were used as in the previous[49] measurements to 12,000. There is nothing particularly noteworthy about the results. No direction exhibited definite hysteresis, and the deviation from a smooth curve was normal enough. The previous corrected compressions at 10,000 were 0.0257, 0.0119, 0.0183, and 0.0241 for the a, b, c, and Y directions respectively, against 0.0258, 0.0120, 0.0187, and 0.0254 found now. The volume decrement listed in Table V was calculated from the linear compression in the b, c, and Y directions.

TABLE V

COMPRESSION OF ORGANIC SINGLE CRYSTALS

Pressure kg/cm²	Sucrose					Rhamnose		Gulonic Lactose
	$\left(\frac{\Delta l}{l_0}\right)_a$	$\left(\frac{\Delta l}{l_0}\right)_b$	$\left(\frac{\Delta l}{l_0}\right)_c$	$\left(\frac{\Delta l}{l_0}\right)_Y$	$\frac{\Delta V}{V_0}$	$\left(\frac{\Delta l}{l_0}\right)_a$	$\left(\frac{\Delta l}{l_0}\right)_c$	$\left(\frac{\Delta l}{l_0}\right)_b$
5,000	.01420	.00662	.01052	.01469	.03151	.01621	.00600	.01586
10,000	.02581	.01202	.01873	.02542	.05518	.02968	.01047	.02784
15,000	.03435	.01677	.02516	.03426	.07434	.04102	.01416	.03753
20,000	.04149	.02097	.03087	.04170	.09074	.05036	.01692	.04588
25,000	.04814	.02480	.03618	.04838	.10552	.05888	.01806	.05411
30,000	.05323	.02831	.04084	.05443	.11866	.06598	.02052	.05870
Deviation	0.34	0.49	0.43	0.39		0.71	0.92	0.48

Rhamnose. This is also monoclinic, requiring four orientations, but only two of the former[50] specimens were still available, those in the a and c directions. In the a orientation there was definite hysteresis in

the normal direction, the maximum width of the loop being 1.43 per cent of the maximum distortion. In the *c* direction there was no definite hysteresis. The previous corrected compressions at 10,000 were 0.02921 and 0.01041 for the *a* and *c* orientations respectively, against 0.02968 and 0.01047 found now.

Gulonic Lactose. This is orthorhombic. Of the three former[41] specimens only that in the *b* direction was now available. There is no definite hysteresis. The former corrected compression at 10,000 for this orientation was 0.0268 against 0.0278 now. The deviation from linearity of this substance is unusually large.

Summary and Discussion

A chief result of the extension of precise and sensitive measurements of compressions to 30,000 kg/cm^2 has been a change in my physical intuition of what to expect. It must still, I think, be accepted as inherently probable that a truly homogeneous substance exposed to a truly hydrostatic pressure can only respond in a smooth fashion, without permanent alteration of dimensions after release of pressure and without hysteresis, and in general with a strain which is a single-value function of pressure. The new insight is that as a matter of fact such completely homogeneous materials are not easy to find, but the majority of substances contain imperfections of one sort or another, perhaps as imperfections of the pure lattice, perhaps as chemical inhomogeneities between the grains, which give rise to small-scale capricious irregularities in their response to pressure in addition to a more or less consistent small-scale hysteresis. The development of such a response would be expected to be more marked the greater the pressure range and the greater the perfection of the measurements. Both of these factors doubtless conspire to make the effects so much more noticeable in the present range of 30,000 kg/cm^2 than in the former range of 12,000.

Acceptance of this point of view demands consideration of one important factor, namely whether the irregularities may not be due to a failure of the pressure to be adequately hydrostatic in the new range because of the very rapidly increasing viscosity under pressure which liquids, especially those with complicated structures, are known to exhibit. A satisfactory answer to this question is possible only now that a quantitative measurement has been made of the viscosity of the transmitting liquid, a mixture of n- and i-pentane, up to 30,000. The results of these measurements, together with those on other liquids, are being published in another number of these Proceedings. It was found that the absolute viscosity of i-pentane

at room temperature at 30,000 kg/cm^2 is about 170 poises. This is about four times the viscosity of glycerine under ordinary circumstances. In view of the slowness with which changes of pressure are produced, about five minutes being consumed in pumping to the final pressure, and the very low corresponding flow velocities in the transmitting liquid which arise only from the volume compression, I believe that any failure of pressure to be truly hydrostatic can now be confidently ruled out as a pertinent factor.

The nature of the hysteresis requires comment. Under normal conditions "hysteresis" by its very derivation signifies a lagging of the effect behind the cause. Under our conditions this would mean that with increasing pressure the decrement of length for a fixed pressure would be numerically less than the decrement under the same decreasing pressure. Although this sort of relationship appears most natural, and is what has been called "normal" above, there is no necessity for it, particularly in those cases where the analysis of the phenomenon into a "cause" and an "effect" is not inevitable. The only necessity would seem to inhere in those situations in which energy relations are involved. Hysteresis may involve an expenditure of energy, and if the coordinates are properly chosen, the area of the hysteresis loop may represent the energy involved in a cycle. Since we are supposing that a steady state is involved, the energy is thermal and the cycle must be dissipative by the second law of thermodynamics. Therefore, if in the steady state there is hysteresis between the *volume* and the pressure, the sense of the hysteresis loop must be "normal." There is, however, no necessity that hysteresis between *length* and pressure should have the normal sense, and in the measurements above, at least four examples were found of an abnormal sense: single crystal tungsten, ruthenium, gold, and columbium. Even in these cases, however, the volume hysteresis must have had the normal sign, so that one can draw the conclusion that these four metals were not isotropically deformed by hydrostatic pressure, but that the hysteresis of the transverse dimensions must have been in the other sense and sufficient to at least compensate the longitudinal hysteresis.

In addition to the irregularities and hysteresis a number of the substances showed cusps or transitions of "the second kind" in the notation of Ehrenfest. These I think must be accepted as an entirely different sort of thing, truly characteristic of the material. The substances which showed these cusps were: nickel, palladium, $Cu_{31}Sn_8$, magnetite, andradite, cobaltite, topaz, and mica. The explanation of these cusps is a task for the theoretical physicist. It is natural to suspect some magnetic effect in the case of nickel and magnetite. In

developing the theory for noncubic crystals it is important that we now have examples both where the discontinuity of derivative is confined to a single direction and where it affects all directions.

It has already been intimated that the irregularities and hysteresis obscure the deviations from linearity that must be supposed to characterize the ideally homogeneous material. In the case of substances with a normal hysteresis loop of the typical lens shape, the best that can be done is doubtless to use the mid-curve of the loop as characterizing the homogeneous material. It seems probable that there is not much danger in doing this. But in the few cases where the loop has some non-typical shape, the best procedure is not obvious. It is to be remarked that embarrassment from this arises in comparatively few cases. Serious uncertainty arises only in the case of materials like some of those examined in this paper in which the deviations from linearity are small because of the absolutely small values of compressibility, and in which irregularities due to inhomogeneities are comparatively large because of the mechanical hardness that usually accompanies incompressibility. Even for these materials the hysteresis loop has the typical lens shape in most cases. The great majority of substances are like those which have been examined in previous papers, in which the compressibilities are higher, the deviations from linearity greater, and the capricious irregularity and hysteresis so much less comparatively, because of the greater mechanical softness, as to occasion little uncertainty as to the correct values for the higher order terms in the compression.

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